**THE SURFACE AGE OF VENUS: APPLYING THE TERRESTRIAL CRATERING RATE** [1]

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The population of Venusian craters having suspected impact-crater morphology has been reported from 115 X $10^6$ $km^2$ of the northern hemisphere of the planet [2, 3]. They estimated the average age of the surface to be approximately 1 b.y. (±0.5 b.y.) on the basis of lunar crater-production curves [4,5] corrected for Venus. Such an old average age is somewhat difficult to reconcile with the similarity in size and mass of Venus and Earth and with Earth's high heat flow and crustal resurfacing rate.

The average crater age of Venus's northern hemisphere may be less than 250 m.y. if we assume equivalence between the recent terrestrial cratering rate and that on Venus for craters ⩾20 km in diameter. For craters larger than this threshold size, below which crater production is significantly affected by the Venusian atmosphere, there are fairly strong observational grounds for concluding that such an equivalence in cratering rates on Venus and Earth may exist. One could argue that the lunar crater-production curves corrected for Venus may be inappropriate for the Venusian surface. The recent cratering rate on Earth, as estimated from astronomical observations of asteroids and determined directly from the terrestrial cratering record, is a factor of about 2 to 3 greater than the equivalent estimated average lunar cratering rate over the last 3.3 b.y. [6,7]. Grieve [7] speculated that this higher cratering rate has been in effect for about the last 1 b.y. Also, Shoemaker [8] noted that the ⩾10-km-diameter cratering record in Phanerozoic rocks of the central United States is indistinguishable from that predicted from astronomical observations of present Earth-crossing asteroids. Thus, it seems reasonable to base the estimate of the cratering rate on Venus for the last 0.5 b.y. on the terrestrial cratering record (e.g., the North American and European cratons), where the record of large (⩾20-km-diameter), dated craters is thought to be most complete.

As of October 1986, 48 asteroids had been discovered that currently pass perihelion inside Earth's orbit; 24 of these asteroids also pass perihelion inside the orbit of Venus. Even though only half of these observed Earth-crossing asteroids overlap the orbit of Venus, the average collision probability per unit surface area per asteroid is 37% higher on Venus than on Earth, the average collision velocity (neglecting atmospheric retardation) is 21% higher on Venus, and the surface gravity is 9.5% lower on Venus. Taking all of these factors into account but neglecting the screening effects of the Venusian atmosphere, the calculated ratio of the rate of crater production by asteroid impact on Venus to the rate on Earth is about 0.9 [9]. After correction for the contribution from the undiscovered class of Venus-crossers on very small orbits, the crater production rate by asteroid impact on Venus is estimated to be 1.0 to 1.1 times the rate on Earth.

In the absence of an atmosphere, the production rate of craters by comet impact would be about 15% higher than the production rate of comet impact craters on Earth [9]. However, the atmosphere of Venus may effectively shield the surface from production of cometary impact craters smaller than about 100 km in diameter. Indeed, it is possible that none of the craters so far observed on Venus were produced by

cometary impact. A major unresolved question in applying either the terrestrial or lunar cratering record to Venus, therefore, is the fraction of terrestrial and lunar craters produced by cometary impact. Recent work suggests that as many as half of the observed terrestrial impact craters could have been produced by comet showers [10]; a smaller fraction, probably about 10% to 20%, has been produced by the background flux of comets [11, 12].

Given the probable role of the dense Venusian atmosphere in reducing the observed number of craters less than about 20 km in diameter [2,3,13], we considered only craters whose diameters are ⩾20 km, ⩾50 km, ⩾100 km, and ⩾140 km in diameter. The production of craters ⩾20 over the past 1 b.y. on the North American and European cratons has been estimated by Grieve [7] to be $5.4 \pm 2.7 \times 10^{-15}$ $km^{-2}$ $yr^{-1}$. This production rate agrees well with that based on astronomical observations of Earth-crossing asteroids [8] and thus was used in the calculation of the Venus crater-retention ages listed in table 1.

For craters larger than 50 km in diameter, the progressively younger Venusian ages reflect the fact that the cumulative size-frequency distribution of Venusian craters is significantly steeper than that of lunar craters. This steepness might be explained as the consequence of nearly complete shielding of the observed surface from comet impacts. Observations of the magnitude-frequency distribution of discovered Earth-crossing asteroids indicate that their size distribution is much steeper than the average size distribution of the projectiles that produced the postmare lunar craters [14]. Most impact craters on the Moon and Earth larger than 50 km in diameter probably have been produced by comet impact. However, the size distribution of Earth-crossing asteroids, by itself, probably is too steep to account for the distribution of Venusian craters. Two possibilities seem likely: (1) some of the Venusian craters greater than 50 km in diameter have been produced by comets, or (2) shielding by the atmosphere has very substantially reduced the production by asteroids of craters in the diameter range of 20-50 km. In either case, the age based on craters ⩾50 km in diameter may be closest to the true age (Table 1).

Given the present uncertainties in the role of both active and inactive comet nuclei in the cratering history of Earth, we conclude that the average age of the observed surface in the northern hemisphere of Venus could be as great as the 450-m.y. mean age of the Earth's crust (oceanic and continental [15]). The surface of Venus might be even older, but no evidence from the crater observations supports an age as great as 1 b.y: if the age of the observed Venusian surface were 1 b.y., it probably should bear the impact scars of a half dozen or more large comet nuclei that penetrated the atmosphere and formed craters well over 100 km in diameter.

In future studies we hope to provide more quantitative constraints on the present crater-production rates and on the cratering history of Venus. Venera 15/16 mapped only about 25% of Venus, the remaining 75% may tell us a completely different story.

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TABLE 1. CRATER-RETENTION AGES ON VENUS DERIVED FROM USE OF CRATERING RATES ON THE TERRESTRIAL CRATONS

| CRATER DIAMETER 1/ >D | NUMBER OF CRATERS 2/ / (RATE) (AREA) | AGE (m.y.) | VARIANCE 3/ | STANDARD DEVIATION |
|---|---|---|---|---|
| >20 km | $\frac{98}{(5.4 \times 10^{-15} \pm 2.7\ km^{-2}\ yr^{-1})\ (1.15 \times 10^{8}\ km^{2})}$ | 158 ± 81 | x(0.25 + 0.01) | x(0.51) |
| >50 km | $\frac{20}{(1.0 \times 10^{-15} \pm 0.50\ km^{-2}\ yr^{-1})\ (1.15 \times 10^{8}\ km^{2})}$ | 174 ± 95 | x(0.25 + 0.05) | x(0.55) |
| >100 km | $\frac{3}{(0.28 \times 10^{-15} \pm 0.14\ km^{-2}\ yr^{-1})\ (1.15 \times 10^{8}\ km^{2})}$ | 94 ± 71 | x(0.25 + 0.333) | x(0.76) |
| >140 km | $\frac{1}{(0.15 \times 10^{-15} \pm 0.075\ km^{-2}\ yr^{-1})\ (1.15 \times 10^{8}\ km^{2})}$ | 54 + 65 / - 54 | x(0.25 + 1.0) | x(1.12) |

1/ >20-km-diameter crater-production rate ($5.4 \pm 2.7 \times 10^{-15}\ km^{-2}\ yr^{-1}$) after [7]. >50, >100, and >140-km-diameter crater-production rates derived from >20-km production rate as $\frac{>D}{>20} = (X^{-1.84})\ (5.4 \times 10^{-15}\ km^{-2}\ yr^{-1})$, assuming crater index of 1.84 [8].

2/ Number of craters on Venus above a given diameter (D) taken from [1,2] amd B.A. Ivanov (personal communication, August 1986, Moscow)

3/ Estimated variance of the age is calculated as the $\sum$ of the variance of the cratering rate and the variance of the crater count (number of craters).